(54) Title: HIGH CAPACITY WIRELESS COMMUNICATION USING SPATIAL SUBCHANNELS

(57) Abstract

In a system and method of digital wireless communication between a base station (B) and a subscriber unit (S), a spatial channel characterized by a channel matrix H couples an adaptive array of Mt antenna elements (1-Mt) at the base station (B) with an adaptive array Mr antenna elements at the subscriber unit (S). The method comprises the step of determining from the channel matrix H a number L of independent spatio-temporal subchannels, and encoding a plurality of information signals into a sequence of transmitted signal vectors. The transmitted signal vectors have Mt complex valued components and are selected to transmit distinct signal information in parallel over the independent subchannels, thereby providing increased communication capacity between the base and the subscriber. The sequence of transmitted signal vectors is transmitted from the base station array (1-Mt), and a sequence of received signal vectors is received at the subscriber array (1-Mr) and are decoded to yield the original information signals. Specific spatio-temporal coding techniques are described that increase system performance.

High Capacity Wireless Communication
Using Spatial Subchannels

RELATED APPLICATIONS

This application claims priority from U.S. provisional applications 60/025,227 and 60/025,228, both filed 08/29/96. Both applications are hereby incorporated by reference.

FIELD OF THE INVENTION

This invention relates generally to digital wireless communication systems. More particularly, it relates to using antenna arrays by both a base station and a subscriber to significantly increase the capacity of wireless communication systems.

BACKGROUND OF THE INVENTION

Due to the increasing demand for wireless communication, it has become necessary to develop techniques for more efficiently using the allocated frequency bands, i.e. increasing the capacity to communicate information within a limited available bandwidth. This increased capacity can be used to enhance system performance by increasing the number of information channels, by increasing the channel information rates and/or by increasing the channel reliability.

FIG. 1 shows a conventional low capacity wireless communication system. Information is transmitted from a base station B to subscribers $S_1, \ldots, S_9$ by broadcasting omnidirectional signals on one of several predetermined frequency channels. Similarly, the subscribers transmit information back to the base station by broadcasting similar signals on one of the frequency channels. In this system, multiple users independently access the system through the

division of the frequency band into distinct subband frequency channels. This technique is known as frequency division multiple access (FDMA).

5   A standard technique used by commercial wireless phone systems to increasing capacity is to divide the service region into spatial cells, as shown in FIG. 2. Instead of using just one base station to serve all users in the region, a collection of base stations $B_1, \ldots, B_7$ are used to independently service
10   separate spatial cells. In such a cellular system, multiple users can reuse the same frequency channel without interfering with each other, provided they access the system from different spatial cells. The cellular concept, therefore, is a simple type of spatial division multiple access (SDMA).

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In the case of digital communication, additional techniques can be used to increase capacity. A few well known examples are time division multiple access (TDMA) and code division multiple access (CDMA). TDMA allows several users to share a
20   single frequency channel by assigning their data to distinct time slots. CDMA is normally a spread-spectrum technique that does not limit individual signals to narrow frequency channels but spreads them throughout the frequency spectrum of the entire band. Signals sharing the band are distinguished by
25   assigning them different orthogonal digital code sequences. These techniques use digital coding to make more efficient use of the available spectrum.

Wireless systems may also use combinations of the above
30   techniques to increase capacity, e.g. FDMA/CDMA and TDMA/CDMA. Although these and other known techniques increase the capacity of wireless communication systems, there is still a need to further increase system performance. Recently, considerable attention has focused on ways to increasing
35   capacity by further exploiting the spatial domain.

One well-known SDMA technique is to provide the base station
with a set of independently controlled directional antennas,
thereby dividing the cell into separate sectors, each
controlled by a separate antenna. As a result, the frequency
5   reuse in the system can be increased and/or cochannel
interference can be reduced. Instead of independently
controlled directional antennas, this technique can also be
implemented with a coherently controlled antenna array, as
shown in FIG. 3. Using a signal processor to control the
10 relative phases of the signals applied to the antenna
elements, predetermined beams can be formed in the directions
of the separate sectors. Similar signal processing can be
used to selectively receive signals only from within the
distinct sectors.

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In an environment containing a significant number of
reflectors (such as buildings), a signal will often follow
multiple paths. Because multipath reflections alter the
signal directions, the cell space experiences angular mixing
20 and can not be sharply divided into distinct sectors.
Multipath can therefore cause cochannel interference between
sectors, reducing the benefit of sectoring the cell. In
addition, because the separate parts of such a multipath
signal can arrive with different phases that destructively
25 interfere, multipath can result in unpredictable signal
fading.

In order to avoid the above problems with multipath, more
sophisticated SDMA techniques have been proposed. For
30 example, U.S. Pat. No. 5,471,647 and U.S. Pat. No. 5,634,199,
both to Gerlach et al., and U.S. Pat. No. 5,592,490 to Barratt
et al. disclose wireless communication systems that increase
performance by exploiting the spatial domain. In the
downlink, the base station determines the spatial channel of
35 each subscriber and uses this channel information to
adaptively control its antenna array to form customized beams,
as shown in FIG. 4A. These beams transmit an information

signal x over multiple paths so that the signal x arrives to
the subscriber with maximum strength. The beams can also be
selected to direct nulls to other subscribers so that
cochannel interference is reduced. In the uplink, as shown in
5   FIG. 4B, the base station uses the channel information to
spatially filter the received signals so that the transmitted
signal x' is received with maximum sensitivity and
distinguished from the signals transmitted by other
subscribers. In this approach the same information signal
10   follows several paths, providing increased spatial redundancy.

In the uplink, there are well known signal processing
techniques for estimating the spatial channel from the signals
received at the base station antenna array, e.g. by using *a
15   priori* spatial or temporal structures present in the signal,
or by blind adaptive estimation. If the uplink and downlink
frequencies are the same, then the spatial channel for the
downlink is directly related to the spatial channel for the
uplink, and the base can use the known uplink channel
20   information to perform transmit beamforming in the downlink.
Because the spatial channel is frequency dependent and the
uplink and downlink frequencies are often different, the base
does not always have sufficient information to derive the
downlink spatial channel information. One technique for
25   obtaining downlink channel information is for the subscriber
to periodically transmit test signals to the base on the
downlink frequency rather than the uplink frequency. Another
technique is for the base to transmit test signals and for the
subscriber to feedback channel information to the base. If
30   the spatial channel is quickly changing due to the relative
movement of the base, the subscriber and/or reflectors in the
environment, then the spatial channel must be updated
frequently, placing a heavy demand on the system. One method
to reduce the required feedback rates is to track only the
35   subspace spanned by the time-averaged channel vector, rather
than the instantaneous channel vector. Even with this

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reduction, however, the required feedback rates are still a large fraction of the signal information rate.

Although these adaptive beamforming techniques require substantial signal processing and/or large feedback rates to determine the spatial channel in real time, these techniques have the advantage that they can navigate the complex spatial environment and avoid, to some extent, the problems introduced by multipath reflections. As a result, an increase in performance is enjoyed by adaptive antenna array systems, due to their use of the spatial dimension. Note, however, that while the base station antenna array can make efficient use of the spatial dimension by selectively directing the downlink signal to the subscriber S, the uplink signal in these systems is spatially inefficient. Typically, the subscriber is equipped with only a single antenna that radiates signal energy in all directions, potentially causing cochannel interference. These communication systems, therefore, do not make optimal use of the spatial dimension to increase capacity.

OBJECTS AND ADVANTAGES OF THE INVENTION

Accordingly, it is a primary object of the present invention to provide a communication system that significantly increases the capacity and performance of wireless communication systems by taking maximum advantage of the spatial domain. Another object of the invention is to provide computationally efficient coding techniques that make optimal use of the spatial dimensions of the channel. These and other objects and advantages will become apparent from the following description and associated drawings.

SUMMARY OF THE INVENTION

These objects and advantages are attained by a method of digital wireless communication that takes maximal advantage of spatial channel dimensions between a base station and a subscriber unit to increase system capacity and performance.

Surprisingly, the techniques of the present invention provide
an increased information capacity in multipath environments.
In contrast, known techniques suffer in the presence of
multipath and do not exploit multipath to directly increase
5   system capacity. In brief, the present invention teaches a
method of wireless communication using antenna arrays at both
the base and subscriber units to transmit distinct information
signals over different spatial channels in parallel, thereby
multiplying the capacity between the base and the subscriber.
10   The present invention also teaches specific spatio-temporal
coding techniques that make optimal use of these additional
spatial subchannels.

Generally, the present invention provides a method of digital
15   wireless communication between a base station and a subscriber
unit, where a spatial channel characterized by a channel
matrix $\mathbf{H}$ couples an array of M_T antenna elements at the base
station with an array of M_R antenna elements at the subscriber
unit. The method comprises the step of determining from the
20   channel matrix $\mathbf{H}$ a number L of independent spatial
subchannels, and encoding a plurality of information signals
into a sequence of transmitted signal vectors. The
transmitted signal vectors have M_T complex valued components
and are selected to distribute distinct signal information
25   over the independent spatial subchannels. The sequence of
transmitted signal vectors is transmitted from the array of M_T
antenna elements at the base station, and a sequence of
received signal vectors is received at the array of M_R antenna
elements at the subscriber unit. The received signal vectors
30   have M_R complex valued components. These received signal
vectors are decoded to yield the information signals.

In another aspect, the invention provides a method that
comprises computing from a set of K original information
35   signals a spatio-temporal coded signal in accordance with a
channel matrix $\mathbf{H}$. The channel matrix $\mathbf{H}$ represents the spatio-
temporal characteristics of the information link between a

base station array of M_T antenna elements and a subscriber
unit array of M_R antenna elements. Signal processing
techniques are used to decompose H into K parallel spatio-
temporal subchannels that can independently carry information
5   signals between the base and subscriber units. After
transmitting the spatio-temporal coded signal over the
channel, it is decoded into a set of K received information
signals that correspond to the K original information signals.
In a preferred embodiment, the K parallel spatio-temporal
10   subchannels are characterized by a set of K spatio-temporal
transmission sequences that are derived from a decomposition
of H into independent modes, and a set of K corresponding
receive sequences. For example, the K spatio-temporal
transmission sequences may be multiples of right singular
15   vectors of H, and the receive sequences may be a matched set
of K spatio-temporal filter sequences that are left singular
vectors of H.

If L is the number of multipath components between the base
20   station and the subscriber unit, then the number K of parallel
spatio-temporal channels is not more than $(N+v) \times M_R$, not more
than $N \times M_T$, and not more than $N \times L$, where $(N+v)$ is a maximum
number of nonzero output samples transmitted for a block of N
symbols. In a preferred embodiment, the original information
25   signals comprise K blocks of N symbols, and the channel matrix
H comprises $M_T \times M_R$ blocks of $N \times (N+v)$ channel matrices H_{ij}.

In some applications of the present invention, the channel
state information (CSI) may not be completely known, or may be
30   expensive to compute. Accordingly, the present invention also
provides a method for facilitating the efficient computation
of the K received information signals from the transmitted
spatio-temporal coded signal by adding cyclic prefixes to the
coded signal prior to transmission.

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DESCRIPTION OF THE FIGURES

FIG. 1 shows a low capacity wireless communication system well known in the prior art.

FIG. 2 illustrates a known technique of spatially dividing a service region into cells in order to increase system capacity.

FIG. 3 illustrates the use of beamforming with an antenna array to divide a cell into angular sectors, as is known in the art.

FIGS. 4A and 4B illustrate state-of-the-art techniques using adaptive antenna arrays for downlink and uplink beamforming, respectively.

FIGS. 5A and 5B show the parallel transmission of distinct information signals using spatial subchannels in downlink and uplink, respectively, as taught by the present invention.

FIGS. 6A and 6B are physical and schematic representations, respectively, of a communication channel for a system with multiple transmitting antennas and multiple receiving antennas, according to the present invention.

FIG. 7 is a block diagram of the system architecture for communicating information over a multiple-input-multiple-output spatial channel according to the present invention.

DETAILED DESCRIPTION

Although the following detailed description contains many specifics for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the following preferred embodiment of the invention is set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

As discussed above in relation to FIGS. 4A and 4B, prior art wireless systems employing an adaptive antenna array at the

base station are multiple-input-single-output (MISO) systems,
i.e. the channel from the base to the subscriber is
characterized by multiple inputs at the transmitting antenna
array and a single output at the receiving subscriber antenna.
Because these MISO systems can exploit some of the spatial
channel, they have an increased capacity as compared to
single-input-single-output (SISO) systems that are discussed
above in relation to FIGS. 1 and 2. It should be noted that
although the MISO systems disclosed in the prior art provide
an increase in overall system capacity by spatially isolating
separate subscribers from each other, these systems do not
provide an increase in the capacity of information transmitted
from the base to a single subscriber, or vice versa. As shown
in FIGS. 4A and 4B, only one information signal is transmitted
between the base and subscriber in both downlink and uplink of
a MISO system. Even in the case where the subscriber is
provided with an antenna array, the prior art suggests only
that this capability would further reduce cochannel
interference. Although the overall system capacity could be
increased, this would not increase the capacity between the
base and a single subscriber.

The present invention, in contrast, is a multiple-input-
multiple-output (MIMO) wireless communication system that is
distinguished by the fact that it increases the capacity of
both uplink and downlink transmissions between a base and a
subscriber through a novel use of additional spatial channel
dimensions. The present inventors have recognized the
possibility of exploiting multiple parallel spatial
subchannels between a base station and a subscriber, thereby
making use of additional spatial dimensions to increase the
capacity of wireless communication. Surprisingly, this
technique provides an increased information capacity and
performance in multipath environments, a result that is in
striking contrast with conventional wisdom.

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FIGS. 5A and 5B illustrate a MIMO wireless communication
system according to the present invention. As shown in FIG.
5A, a base station B uses adaptive antenna arrays and spatial
processing to transmit distinct downlink signals x_1, x_2, x_3
through separate spatial subchannels to a subscriber unit S
which uses an adaptive array and spatial processing to receive
the separate signals. In a similar manner, the subscriber S
uses an adaptive array to transmit distinct uplink signals
x'_1, x'_2, x'_3 to the base B over the same spatial subchannels.
As the multipath in the environment increases, the channel
acquires a richer spatial structure that allows more
subchannels to be used for increased capacity.

It is important to note that the simple assignment of the
distinct signals to the distinct spatial paths in a one-to-one
correspondence, as illustrated above, is only one possible way
to exploit the additional capacity provided by the spatial
subchannel structure. For example, coding techniques can be
used to mix the signal information among the various paths.
In addition, the present inventors have developed techniques
for coupling these additional spatial dimensions to available
temporal and/or frequency dimensions prior to transmission.
Although such coupled spatio-temporal coding techniques are
more subtle than direct spatial coding alone, they provide
better system performance, as will be described in detail
below.

In order to facilitate an understanding of the present
invention and enable those skilled in the art to practice it,
the following description includes a teaching of the general
principles of the invention, as well as implementation
details. First we develop a compact model for understanding
frequency dispersive, spatially selective wireless MIMO
channels. We then discuss their theoretical information
capacity limits, and propose spatio-temporal coding structures
that asymptotically achieve theoretical channel capacity. In
particular, a spatio-temporal vector coding (STVC) structure

for burst transmission is disclosed, as well as a more
practical, reduced complexity, discrete matrix multitone
(DMMT) space-frequency coding structure. Both STVC and DMMT
are shown to achieve the theoretical channel capacity as the
5   burst duration increases.

In its preferred implementations, the present invention makes
use of many techniques and devices well known in the art of
adaptive antenna arrays systems and associated digital
10   beamforming signal processing. These techniques and devices
are described in detail in U.S. Pat. No. 5,471,647 and U.S.
Pat. No. 5,634,199, both to Gerlach et al., and U.S. Pat. No.
5,592,490 to Barratt et al., which are all incorporated herein
by reference. In addition, a comprehensive treatment of the
15   present state of the art is given by John Livita and Titus
Kwok-Yeung   Lo   in   *Digital   Beamforming   in   Wireless
Communications* (Artech House Publishers, 1996). Accordingly,
the following detailed description focuses upon the specific
signal processing techniques which are required to enable
20   those skilled in the art to practice the present invention.

Consider a communication channel for a system with M_T
transmitting antennas at a base B and M_R receiving antennas at
a subscriber S, as illustrated in FIGS. 6A and 6B. The
25   channel input at a sample time k can be represented by an M_T
dimensional column vector

$\mathbf{z}(k) = [z_1(k), \ldots, z_{M_T}(k)]^T,$

30   and the channel output and noise for sample k can be
represented, respectively, by M_R dimensional column vectors

$\mathbf{x}(k) = [x_1(k), \ldots, x_{M_R}(k)]^T,$
and
35   $\mathbf{n}(k) = [n_1(k), \ldots, n_{M_R}(k)]^T.$

The communication over the channel $\mathbf{H}$ may then be expressed as
a vector equation

$$\mathbf{x}(k) = \mathbf{H}\mathbf{z}(k) + \mathbf{n}(k),$$

where the MIMO channel matrix is

$$\mathbf{H} = \begin{pmatrix} h_{1,1} \cdots h_{1,M_T} \\ \vdots \qquad \vdots \\ h_{M_R,1} \cdots h_{M_R,M_T} \end{pmatrix}.$$

Each matrix element h_{ij} represents the SISO channel between
the ith receiver antenna and the jth transmitter antenna. Due
to the multipath structure of the spatial channel, orthogonal
spatial subchannels can be determined by calculating the
independent modes (e.g. eigenvectors) of the channel matrix $\mathbf{H}$.
These spatial subchannels can then be used to transmit
independent signals and increase the capacity of the
communication link between the base B and the subscriber S.
Because the multipath introduces time delays, however, a
spatial decomposition alone will result in temporal mixing of
the signals. It is more appropriate, therefore, to perform a
more general spatio-temporal analysis of the channel.

Let $\{z_j(n)\}$ be a digital symbol sequence to be transmitted
from the jth antenna element, $g(t)$ a pulse shaping function
impulse response, and T the symbol period. Then the signal
applied to the jth antenna element at time t is given by

$$s_j(t) = \sum_n z_j(n)g(t-nT)$$

The pulse shaping function is typically the convolution of two
separate filters, one at the transmitter and one at the
receiver. The optimum receiver filter is a matched filter. In
practice, the pulse shape is windowed resulting in a finite
duration impulse response. We assume synchronous complex
baseband sampling with symbol period T. We define n_0 and $(\nu+1)$

to be the maximum lag and length over all paths l for the
windowed pulse function sequences $\{g(nT - \tau_l)\}$. To simplify
notation, it is assumed that $n_0 = 0$, and the discrete-time
notation $g(nT - \tau_l) = g_l(n)$ is adopted.

When a block of N data symbols are transmitted, N+v non-zero
output samples result beginning at time sample k-N+1 and
ending with sample k+v. The composite channel output can now
be written as an $M_R N (N+v)$ dimensional column vector with all
time samples for a given receive antenna appearing in order so
that

$$\mathbf{x}(k) = [x_1(k-N+1),\ldots,x_1(k+v),\ldots,x_{M_R}(k-N+1),\ldots,x_{M_R}(k+v)]^T,$$

with an identical stacking for the output noise samples $\mathbf{n}(k)$.
Similarly, the channel input is an $M_T N$ dimensional column
vector written as

$$\mathbf{z}(k) = [z_1(k-N+1),\ldots,z_1(k),\ldots,z_{M_T}(k-N+1),\ldots,z_{M_T}(k)]^T,$$

The spatio-temporal communication over the channel $\mathbf{H}$ may then
be expressed as a vector equation

$$\mathbf{x}(k) = \mathbf{H}\mathbf{z}(k) + \mathbf{n}(k),$$

where the MIMO channel matrix

$$\mathbf{H} = \begin{pmatrix} \mathbf{H}_{1,1} \cdots \mathbf{H}_{1,M_T} \\ \vdots \qquad \vdots \\ \mathbf{H}_{M_R,1} \cdots \mathbf{H}_{M_R,M_T} \end{pmatrix}$$

is composed of SISO sub-blocks $\mathbf{H}_{ij}$ with each sub-block
possessing the well known Toeplitz form.

We will now discuss the information capacity for the spatio-
temporal channel developed above. The following analysis
assumes that the noise $\mathbf{n}(k)$ is additive white Gaussian noise
(AWGN) with covariance $\sigma^2 \mathbf{I}$. Each channel use consists of an N

symbol burst transmission and the total average power radiated
from all antennas and all time samples is constrained to less
than a constant.

Write the singular value decomposition (SVD) of the channel
matrix as $\mathbf{H} = \mathbf{V}_H \Lambda_H \mathbf{U}_H^*$, with the jth singular value denoted $\lambda_{H,j}$.
Write the spatio-temporal covariance matrix for $\mathbf{z}(k)$ as $\mathbf{R}_z$
with eigenvalue decomposition $\mathbf{R}_z = \mathbf{V}_z \Lambda_z \mathbf{U}_z^*$, and eigenvalues $\lambda_{z,j}$.

It can be demonstrated that the information capacity for the
discrete-time spatio-temporal communication channel defined
above is given by

$$C = \sum_{n=1}^{N \mathcal{K} M_T} \log \left(1 + \frac{\lambda_{z,n} |\lambda_{H,n}|^2}{\sigma^2} \right)$$

where $\lambda_{z,n}$ is given by the spatio-temporal water-filling
solution. Motivated by this result, the inventors devised the
following temporal vector coding technique. By appropriately
selecting up to $N \mathcal{K} M_T$ spatio-temporal transmission vectors that
are multiples of the right singular vectors of $\mathbf{H}$, and
receiving with up to $N \mathcal{K} M_T$ matched spatio-temporal filter
vectors that are the left singular vectors of $\mathbf{H}$, up to $N \mathcal{K} M_T$
parallel spatio-temporal subchannels are constructed for
communicating information over the channel. Mathematically,
this STVC channel is derived as follows. Substituting
$\mathbf{H} = \mathbf{V}_H \Lambda_H \mathbf{U}_H^*$ into the original equation $\mathbf{x}(k) = \mathbf{H} \mathbf{z}(k) + \mathbf{n}(k)$ for the
channel gives

$$\mathbf{x}(k) = \mathbf{V}_H \Lambda_H \mathbf{U}_H^* \mathbf{z}(k) + \mathbf{n}(k),$$

Left multiplication by $\mathbf{V}_H^*$ yields

$$\mathbf{V}_H^* \mathbf{x}(k) = \Lambda_H \mathbf{U}_H^* \mathbf{z}(k) + \mathbf{V}_H^* \mathbf{n}(k),$$

which yields the STVC channel when rewritten as

$$\hat{\mathbf{x}}(k) = \Lambda_H \hat{\mathbf{z}}(k) + \hat{\mathbf{n}}(k),$$

where $\hat{\mathbf{z}}(k) = \mathbf{U}_H^* \mathbf{z}(k)$, $\hat{\mathbf{x}}(k) = \mathbf{V}_H^* \mathbf{x}(k)$ and $\hat{\mathbf{n}}(k) = \mathbf{V}_H^* \mathbf{n}(k)$.

By analyzing the ranks of the above matrices, it can be demonstrated that the maximum number of finite amplitude parallel spatio-temporal channel dimensions, K, that can be created to communicate over the far field channel defined above is equal to min { $N \aleph L$, $(N+v) \aleph M_R$, $N \aleph M$ }, where L is the number of multipath components. Thus, multipath is an advantage in far-field MIMO channels. If the multipath is large (L   1), the capacity can be multiplied by adding antennas to both sides of the radio link. This capacity improvement occurs with no penalty in average radiated power or frequency bandwidth because the number of parallel channel dimensions is increased. In practice, an adaptive antenna array base station, such as that described by Barratt et al., is modified to implement the above vector coding scheme. In particular, a signal processor is designed to perform a spatio-temporal transform of information signals in accordance with the above equations so that they may be transmitted through the independent parallel subchannels and decoded by the subscriber.

The space-time vector coding solution described above requires a computation of the singular value decomposition of an $(N+v) \aleph M_R \times N \aleph M_T$ matrix. Since this computation can be complex, the present inventors have developed an optimal space-time communication structure that requires less computational complexity to implement. In particular, complexity can be reduced by using a coding structure similar to the discrete multi-tone (DMT) standard. DMT is in widespread use for wired SISO channels. DMT has also been applied to wired MISO channels, as described in U.S. Pat. No. 5,625,651 which is hereby incorporated by reference. The present inventors have generalized DMT to the MIMO case and

adapted it to wireless channels to obtain a novel space-
frequency coding structure that results in a matrix of
transmission and reception vector solutions for each discrete
Fourier transform (DFT) frequency index. Because this new
coding scheme has been generalized to MIMO channels
characterized by a channel matrix, it is called discrete
matrix multi-tone (DMMT).

In DMMT, N data symbols are again transmitted during each
channel usage. However, a cyclic prefix is added to the data
so that the last v data symbols are transmitted from each
antenna element prior to transmitting the full block of N
symbols. By receiving only N time samples at the output of
each antenna element, ignoring the first and last v output
samples, the MIMO channel submatrices $\hat{H}_{ij}$ now appear as cyclic
structures:

$$
\hat{H}_{i,j} = \begin{pmatrix}
h(v) & \cdots & h(0) & 0 & 0 \cdots 0 & 0 & 0 & 0 \\
0 & h(v) & & h(0) & 0 \cdots 0 & 0 & 0 & 0 \\
\vdots & & & & \vdots & \vdots & & \vdots \\
0 & & & & 0 \cdots 0 & & & 0 \\
0 & \cdots & 0 & 0 & 0 \cdots 0 & h(v) & \cdots & h(0) \\
& & & & \vdots & \vdots & \vdots & & \vdots \\
h(v-1) & \cdots & h(0) & 0 & 0 \cdots 0 & \cdots & 0 & h(v)
\end{pmatrix}
$$

Given the cyclic SISO channel blocks, the channel matrix can
be diagonalized with a relatively simple three step procedure.
First post multiply $\hat{H}$ with the $N M_T \times N M_T$ block diagonal
inverse discrete Fourier transform (IDFT) matrix $F^{*(M_T)}$ where
each diagonal block is the unitary $N \times N$ IDFT matrix F^*. The
next step is to premultiply $\hat{H}$ by a similar $N M_R \times N M_R$ block
diagonal DFT matrix $F^{(M_R)}$ where the diagonal submatrices F are
$N \times N$ DFT matrices. With the well known result that the
discrete Fourier transform basis vectors form the orthonormal
singular vectors of the cyclic matrices $\hat{H}_{ij}$, the new channel

matrix resulting from the IDFT post multiplication and the DFT premultiplication is

$$\mathbf{F}^{(M_R)}\hat{\mathbf{H}}\mathbf{F}^{*(M_T)} = \begin{pmatrix} \Gamma_{1,1} \cdots \Gamma_{1,M_T} \\ \vdots \quad\quad \vdots \\ \Gamma_{M_R,1} \cdots \Gamma_{M_R,M_T} \end{pmatrix}$$

where $\Gamma_{i,j}$ is the diagonal matrix containing the singular values $\gamma_{i,j,n}$ of the cyclic channel submatrix $\hat{\mathbf{H}}_{ij}$. Premultiplication and postmultiplication by a permutation matrix $\mathbf{P}$ yields the block diagonal matrix

$$\mathbf{P}\mathbf{F}^{(M_R)}\hat{\mathbf{H}}\mathbf{F}^{*(M_T)}\mathbf{P} = \begin{pmatrix} \mathbf{B}_1 & & 0 \\ & \aleph \cdot & \\ 0 & & \mathbf{B}_N \end{pmatrix}$$

where

$$\mathbf{B}_n = \begin{pmatrix} \gamma_{1,1,n} \cdots \gamma_{1,M_T,n} \\ \vdots \quad\quad \vdots \\ \gamma_{M_R,1,n} \cdots \gamma_{M_R,M_T,n} \end{pmatrix}$$

is the $M_R \times M_T$ space-frequency channel evaluated at DFT index n. Given the SVD of $\mathbf{B}_n = \mathbf{V}_{B,n}\Lambda_{B,n}\mathbf{U}_{B,n}^*$, the diagonal DMMT channel matrix $\hat{\mathbf{H}}$ is finally obtained by post multiplying by $\mathbf{U}_B^{(M_T)}$ and premultiplying by $\mathbf{V}_B^{*(M_R)}$ to obtain

$$\Lambda_{\hat{H}} = \mathbf{V}_B^{*(M_R)}\mathbf{P}\mathbf{F}^{(M_R)}\hat{\mathbf{H}}\mathbf{F}^{*(M_T)}\mathbf{P}\mathbf{U}_B^{(M_T)} = \begin{pmatrix} \Lambda_{\hat{H},1} & & 0 \\ & \aleph \cdot & \\ 0 & & \Lambda_{\hat{H},N} \end{pmatrix}$$

where $\mathbf{U}_B^{(M_T)}$ is block diagonal containing the right singular matrices of the $\mathbf{B}_n$ matrices, $\mathbf{V}_B^{*(M_R)}$ is block diagonal containing the left singular matrices of the $\mathbf{B}_n$ matrices, and each of the diagonal submatrices $\Lambda_{\hat{H},n}$ contains the DMMT spatial sub-channel amplitudes, $\lambda_{\hat{H},n,j}$ for DFT bin n. The parallel channel DMMT equation is then

$$\hat{\mathbf{x}}(k) = \Lambda_{\hat{H}}\hat{\mathbf{z}}(k) + \hat{\mathbf{n}}(k),$$

5   where $\mathbf{z}(k)$ is the dimension $N \times M_T$ input symbol vector, $\hat{\mathbf{x}}(k)$ is
     the dimension $N \times M_R$ output symbol vector, and $\hat{\mathbf{n}}(k)$ is the
     dimension $N \times M_R$ equivalent output noise vector after the DFT
     and spatial orthogonalization operations are performed. A
     block diagram architecture that implements this DMMT space-
10   frequency channel decomposition is presented in FIG. 7. The
     left portion of the diagram corresponds to the application of
     the operators $\mathbf{F}^{*(M_T)}\mathbf{P}\mathbf{U}_B^{(M_T)}$ on the signal $\hat{\mathbf{z}}(k)$. These
     operations are performed by a signal processor at the
     transmitter. The right portion of the diagram corresponds to
15   the application of the operators $\mathbf{V}_B^{*(M_R)}\mathbf{P}\mathbf{F}^{(M_R)}$ on the received
     signals to recover a received information signal $\hat{\mathbf{x}}(k)$. These
     operations are performed by a signal processor at the
     receiver. The central matrix $\hat{\mathbf{H}}$ corresponds to the spatial
     channel itself. By construction, the signal processing
20   operations result in a direct relationship between the
     received and transmitted information signals, as indicated by
     the fact that the matrix $\Lambda_{\hat{H}}$ in the parallel channel DMMT
     equation is diagonal.

25   This coding scheme significantly reduces the signal processing
     complexity required at the transmitter and receiver to
     diagonalize all space-time subchannels for each data block.
     In particular, this asymptotically optimal space-frequency
     MIMO DMMT information transmission technique has a complexity
30   advantage of approximately N^2 as compared to the vector coding
     case. Moreover, since all of the matrix operations involved in
     creating the diagonal DMMT channel are invertible, the
     capacity of the DMMT channel is unchanged from that of the
     original cyclic sub-block matrix $\hat{\mathbf{H}}$. Thus, compared to STVC,
35   the only capacity decrease for the DMMT space-time coding
     solution is due to the radiated power penalty required to
     transmit the cyclic prefix. This capacity penalty, however,

becomes small for large N. Thus, this new communications
structure offers the advantage of very large increases in
capacity without penalty in total average transmitted power or
bandwidth.

In order to perform transmit beamforming, the base station
signal processor computes spatio-temporal downlink subchannel
information from downlink channel information fed back from
the subscriber. The downlink signal information is then
encoded in accordance with this computed downlink subchannel
information. Similarly, the subscriber performs the same
functions for the uplink channel using information fed back
from the base. Because the present invention provides
techniques for efficient channel estimation and increased
channel capacity, the base and subscriber can both quickly
estimate the channel and exchange channel information over the
increased capacity channels, possibly at a rate slower than
that of information data. As a result, both the base and
subscriber can maintain a high degree of spatial resolution in
transmit beamforming, thereby significantly reducing cochannel
interference from other base stations or subscribers. As a
result of this high degree of spatial discrimination in both
transmission and reception, many more base stations and
subscribers can share the same region of space while using the
same frequency channel. Consequently, in addition to
increasing the capacity of the channel between any two arrays,
the present invention also increases system wide capacity by
significantly reducing cochannel interference.

The teaching contained in this description can easily be
extended to channels where the noise is not white but is
highly structured as in the case of additive co-channel
interference. In this case, large gains in cellular network
capacity result from the ability to null interference at the
receiver and the ability to constrain radiated interference
power at the transmitter. These spatial coding techniques can
also be applied to single frequency subchannel systems with

flat fading, conventional analog multicarrier transmission channels, or CDMA channels where each code delay can be decomposed into orthogonal subchannels provided that there is sub-chip multipath. The concepts of the present invention can
5   also be applied to a more general class of channels where the antenna array is distributed over large distances and the propagation does not follow far field behavior. Finally, other communication media such as wire-line, acoustic media, and optical media will experience the same basic communication
10   system benefits when spatio-temporal MIMO channel structures are employed. Thus, it will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined
15   by the following claims and their legal equivalents.

CLAIMS

What is claimed is:

1.   A method of digital wireless communication between a base station and a subscriber unit, the method comprising:

determining from channel information a number L of independent spatial subchannels, wherein the channel information comprises spatial information relating to a spatial channel coupling an array of M_T antenna elements at the base station with an array of M_R antenna elements at the subscriber unit;

encoding a plurality of information signals into a sequence of transmitted signal vectors, wherein the transmitted signal vectors have M_T complex valued components and are selected to send distinct information signal over the independent spatial subchannels;

transmitting the sequence of transmitted signal vectors from the array of M_T antenna elements at the base station;

receiving a sequence of received signal vectors at the array of M_R antenna elements at the subscriber unit, wherein the received signal vectors have M_R complex valued components; and

decoding the received signal vectors to recover the information signals.

2.   The method of claim 1 further comprising transmitting the channel information from the subscriber to the base.

3.   The method of claim 1 wherein the channel information comprises a spatio-temporal channel matrix.

4.   The method of claim 1 wherein the number L of independent spatial subchannels is equal to the number of multiple signal paths between the base and the subscriber.

5.   The method of claim 1 wherein the encoding step comprises scaling the information signals by complex numbers,

permuting the scaled information signals and inverse
Fourier transforming the permuted scaled information
signals, and wherein the decoding step comprises Fourier
transforming the received signals, permuting the Fourier
transformed received signals, and scaling the permuted
Fourier transformed received signals.

6.   A method of digital wireless communication between a base
station and a subscriber unit, the method comprising:
computing from a set of K original information signals a
      spatio-temporal coded signal in accordance with a channel
      matrix H having K parallel spatio-temporal subchannels;
transmitting the spatio-temporal coded signal from a base
      station array of M_T antenna elements through a channel
      corresponding to the channel matrix H to a subscriber
      unit array of M_R antenna elements; and
computing from the transmitted spatio-temporal coded signal a
      set of K received information signals.

7.   The method of claim 6 wherein K is not more than
      $(N+v) \times M_R$, not more than $N \times M_T$, and not more than
      $N \times L$, where L is a maximum number of multipath
      components between the base station and the subscriber
      unit, and where $(N+v)$ is a maximum number of nonzero
      output samples transmitted for a block of N symbols.

8.   The method of claim 6 wherein the original information
      signals comprise K blocks of N symbols, and the channel
      matrix H comprises $M_T \times M_R$ blocks of $N \times (N+v)$ channel
      matrices H_{ij}, where $(N+v)$ is a maximum number of nonzero
      output samples transmitted for a block of N symbols.

9.   The method of claim 6 wherein cyclic prefixes are added
      to the coded signal prior to the transmitting step,
      thereby facilitating the efficient computation of the K
      received information signals from the transmitted spatio-
      temporal coded signal.

10. The method of claim 6 wherein the K parallel spatio-
     temporal subchannels are characterized by a set of K
     spatio-temporal transmission sequences that are derived
     from a decomposition of **H** into independent modes.

11. The method of claim 6 wherein the K parallel spatio-
     temporal subchannels are characterized by a set of K
     spatio-temporal transmission sequences that are multiples
     of right singular vectors of **H**, and matched set of K
     spatio-temporal filter sequences that are left singular
     vectors of **H**.

12. A digital wireless communication system comprising:
     a base station comprising a base station antenna array and a
        base station signal processor coupled to the base station
        antenna array;
     a subscriber unit comprising a subscriber antenna array
        coupled through a wireless channel to the base station
        antenna array and a subscriber signal processor coupled
        to the subscriber antenna array;
     wherein the base station signal processor computes spatio-
        temporal downlink subchannel information from downlink
        channel information received from the subscriber, and
        encodes downlink signal information in accordance with
        the computed downlink subchannel information; and
     wherein the subscriber signal processor computes spatio-
        temporal uplink subchannel information from uplink
        channel information received from the base station, and
        encodes uplink signal information in accordance with the
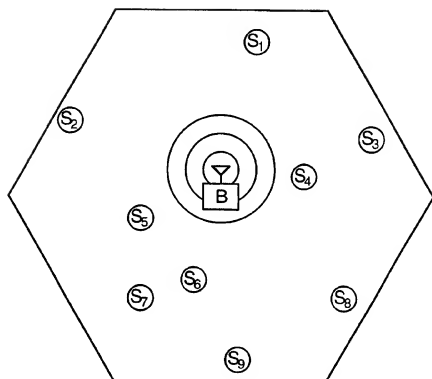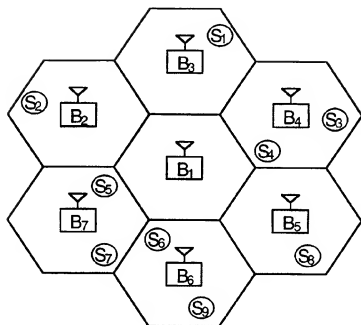   computed uplink subchannel information.
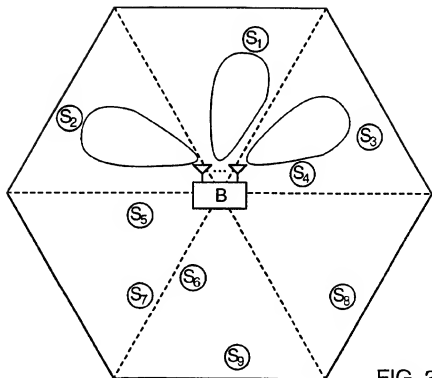
FIG. 1
(PRIOR ART)

FIG. 2
(PRIOR ART)

FIG. 3
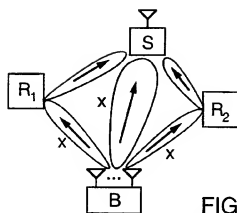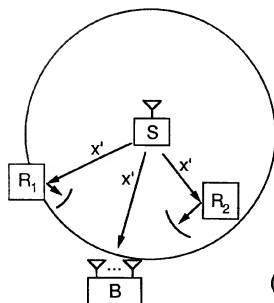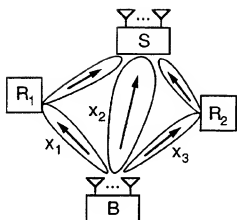(PRIOR ART)

FIG. 4A
(PRIOR ART)

FIG. 4B
(PRIOR ART)

5/7

FIG. 5A
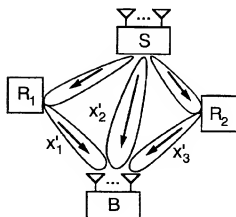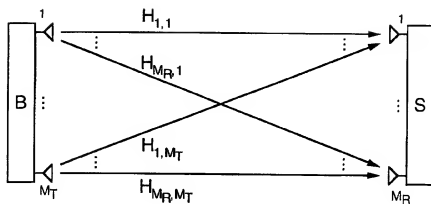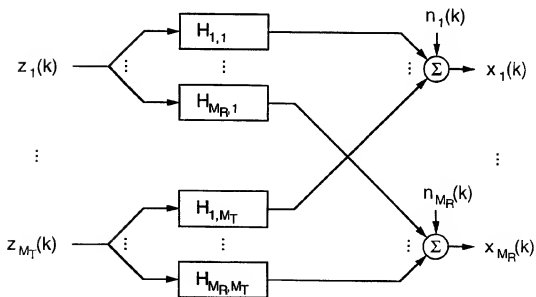

FIG. 5B

FIG. 6A

FIG. 6B
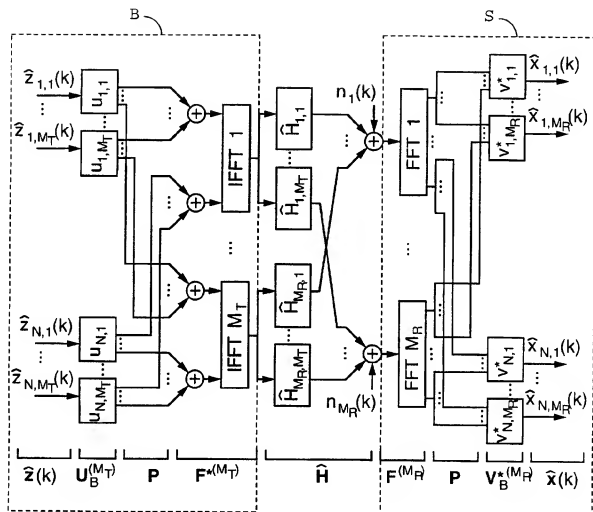
FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/15363

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H04B 1/38; H04M 1/00
US CL :455/562, 101, 103, 272
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 455/562, 101, 103, 272, 504, 506, 65, 132; 375/347

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4,710,944 A (NOSSEN) 01 December 1987, columns 3-8, figures 1 and 5.	1-12
X	US 5,548,819 A (ROBB) 20 August 1996, columns 10-13, figures 1a-1b.	1-12
A,P	US 5,649,287 A (FORSSEN ET AL) 15 July 1997, figure 5.	1-12

☐ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
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"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09 OCTOBER 1997	1 7 NOV 1997

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